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SOLID NEON SOURCES FOR PLASMAS AND X-RAY LASERS(U)  
NAVAL RESEARCH LAB WASHINGTON DC R H DIXON ET AL.  
30 APR 85 NRL-NR-5534 DE-A108-79DP40092

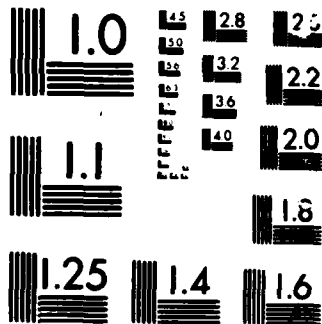
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NRL Memorandum Report 5534

## Solid Neon Sources for Plasmas and X-Ray Lasers

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Plasma Physics Division*

April 30, 1985

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| REPORT DOCUMENTATION PAGE   |       |   |  |  |
|---|-------|---|--|--|
| 1a REPORT SECURITY CLASSIFICATION<br><b>UNCLASSIFIED</b>  |       |   | 1b RESTRICTIVE MARKINGS  |  |
| 2a SECURITY CLASSIFICATION AUTHORITY  |       |   | 3 DISTRIBUTION / AVAILABILITY OF REPORT  |  |
| 2b DECLASSIFICATION / DOWNGRADING SCHEDULE  |       |   | Approved for public release; distribution unlimited.                             |  |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S)<br><b>NRL Memorandum Report 5534</b>   |       |   | 5 MONITORING ORGANIZATION REPORT NUMBER(S)                                       |  |
| 6a NAME OF PERFORMING ORGANIZATION<br><b>Naval Research Laboratory</b>  |       | 6b OFFICE SYMBOL<br>(If applicable)<br><b>Code 4730</b> |  | 7a NAME OF MONITORING ORGANIZATION   |
| 6c ADDRESS (City, State, and ZIP Code)<br><b>Washington, DC 20375-5000</b>  |       |   | 7b ADDRESS (City, State, and ZIP Code)   |  |
| 8a NAME OF FUNDING / SPONSORING ORGANIZATION<br><b>Department of Energy</b>   |       | 8b OFFICE SYMBOL<br>(If applicable)                     |  | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br><b>DE-AI0879DP40092 PR #08-85DP40092.001</b> |
| 8c ADDRESS (City, State, and ZIP Code)<br><b>Washington, DC 20545</b>   |       |   | 10 SOURCE OF FUNDING NUMBERS   |  |
|   |       |   | PROGRAM<br>ELEMENT NO  | PROJECT<br>NO  |
|   |       |   | TASK<br>NO.  | WORK UNIT<br>ACCESSION NO.<br><b>DN220-133</b>   |
| 11 TITLE (Include Security Classification)<br><b>Solid Neon Sources for Plasmas and X-Ray Lasers</b>  |       |   |  |  |
| 12 PERSONAL AUTHOR(S)<br><b>Dixon, R.H., Ford, J.L., Lee, T.N. and Elton, R.C.</b>  |       |   |  |  |
| 13a TYPE OF REPORT<br><b>Interim</b>  |       | 13b TIME COVERED<br>FROM TO                             |  | 14 DATE OF REPORT (Year, Month, Day)<br><b>1985 April 30</b>                                   |
| 15 PAGE COUNT<br><b>14</b>  |       |   |  |  |
| 16 SUPPLEMENTARY NOTATION   |       |   |  |  |
| 17 COSATI CODES   |       |   | 18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number) |  |
| FIELD   | GROUP | SUB-GROUP   |  |  |
|   |       |   |  |  |
|   |       |   |  |  |
| 19 ABSTRACT (Continue on reverse if necessary and identify by block number)<br><br>A thin layer of frozen neon is condensed onto a cryogenically cooled substrate for use in generating a neon plasma for x-ray laser research. The freezing process and quasi-equilibrium state of the layer are discussed with a phase diagram. Spectral purity of a neon plasma formed by laser irradiation is demonstrated with grazing incidence x-ray spectroscopy. Control of the layer thickness is possible to the point that a substrate spectrum is also obtained. |       |   |  |  |
| 20 DISTRIBUTION / AVAILABILITY OF ABSTRACT<br><input checked="" type="checkbox"/> UNCLASSIFIED / UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS   |       |   | 21 ABSTRACT SECURITY CLASSIFICATION<br><b>UNCLASSIFIED</b>                       |  |
| 22a NAME OF RESPONSIBLE INDIVIDUAL<br><b>R. C. Elton</b>  |       |   | 22b TELEPHONE (Include Area Code)<br><b>(202) 767-2754</b>                       | 22c OFFICE SYMBOL<br><b>Code 4733</b>  |

DD FORM 1473, 84 MAR

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| DTIC TAB           | <input type="checkbox"/>            |
| Unannounced        | <input type="checkbox"/>            |
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| Availability Codes |                                     |
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# SOLID NEON SOURCES FOR PLASMAS AND X-RAY LASERS

## I. INTRODUCTION

For various applications including x-ray lasers and inertial confinement fusion, it is desirable to create highly ionized and very dense plasmas from elements such as neon that normally exist only in the gaseous state. Plasmas created by focused high power laser beams for such purposes are usually formed from solid targets at the critical electron density ( $\sim 10^{21} \text{ cm}^{-3}$  for  $1 \mu\text{m}$  wavelength) where beam absorption is a maximum; and they are often diagnosed by observations in the vacuum ultraviolet spectral region, where high pressure gaseous atmospheres are opaque. Very small ( $\leq 100 \mu\text{m}$  diameter) glass microspheres have been filled successfully with neon (and argon) at high pressures and used for compression diagnostics when irradiated and imploded in vacuum surroundings. However, for the pure elongated plasmas of lengths extending to centimeters such as required for x-ray lasers, solid (frozen) targets appear to be a desirable alternate approach.<sup>1</sup> Another alternative is ion implantation into solid materials<sup>2</sup> using ion accelerators; however the concentration is only about 10% and the ions are often located in a thin layer below the surface from which the high temperature plasma is created.<sup>3,4</sup>

The primary goal of this particular effort was the creation of a neon plasma at an ion density of  $\sim 10^{19} \text{ cm}^{-3}$  in the helium-like  $\text{Ne}^{8+}$  species, with population inversion (for x-ray lasing from the  $n=3$  and  $n=4$  states to lower states) created by selective absorption pumping with a  $1.1 \text{ nm}$  wavelength photon from  $\text{Na}^{9+}$  ions in a nearby plasma.<sup>1,5-8</sup> This particular combination has been chosen as a test case for matched-line photon pumping, both because of the almost exact and accurately-calculated wavelength match between the pumping and the absorbing transitions<sup>9</sup>, and also because of the adjacent

Manuscript approved January 4, 1985.

charge states of these ions, which reduces the problems in producing spatial and temporal simultaneity. Other combinations involving neon ions also exist,<sup>1</sup> but with less-exact matches.

## II. TECHNIQUE

A commercially available<sup>10</sup> 28-inch long liquid helium refrigerated cold tip was mounted with a three dimensional micromanipulator/positioner into a 40 cm diameter vacuum target chamber. A 1.5 cm thick copper disc of 2.5 cm diameter was screwed onto the cold tip, compressing an indium washer to insure good thermal contact. This copper disc held interchangeable substrates for the neon coatings. A radiation shield maintained at liquid nitrogen temperature was installed around the cold tip, as indicated in Fig. 1.

Formation of the frozen neon layer is best described with the help of a pressure versus temperature phase diagram<sup>11,12</sup> as shown in Fig. 2. The formation of frozen neon onto the substrate directly from surrounding gas, either in a static filling or a nozzle-fed flowing configuration, was not successful because the neon gas being cooled for condensation at the cold tip was continually replaced by warmer gas. To remedy this, the copper disc was fitted with a sealed nylon annular ring which extends radially to the radiation shield (Fig. 1). In the coating procedure, a lucite cap is first raised (+y direction, Fig. 1) and then pressed against the nylon ring with an "O"-ring seal by translating the cold tip (+ z direction). This cap includes a small reservoir, which is evacuated, flushed, and then filled (through a liquid nitrogen cooled trap) with neon to a pressure of 1-1.5 atmospheres (760-1140 Torr); and the liquid and then solid neon phase formations are

observed visually while the tip is cooled at constant pressure to  $<25\text{ }^{\circ}\text{K}$  (measured by a thermocouple at the tip), which is indicated by point A in Fig. 2. A reservoir maintains the neon gas concentration almost constant during this procedure. The thermal insulation property of the nylon annular ring was found to be essential for the subsequent removal of the cap under the extreme cold condition. After formation of a solid layer of neon, the reservoir is partially evacuated, the tip temperature decreases to  $<9\text{ }^{\circ}\text{K}$  (point B in Fig. 2), and the neon surface layer is maintained in equilibrium.

In order to expose the solid neon surface to the laser beam and to allow access for vacuum diagnostics, the cryogenic assembly is next retracted along the  $-z$  axis (Fig. 1) and the reservoir assembly is lowered in the  $-y$  direction. After this, an ambient pressure of  $10^{-6}$ - $10^{-5}$  Torr is maintained for insulation against conductive heat flow from the walls of the chamber. Even at such low pressure, some radiative heating of the exposed surface occurs, and a typical measured tip temperature is in the  $6$ - $10\text{ }^{\circ}\text{K}$  range (C in Fig. 2). A vapor phase may exist at C such that the solid neon state is transient, imposing a challenge to maintain the solid layer against sublimation for an interval sufficient to complete the experiment. An explanation of such quasi-equilibrium operation is given in Section III below.

A major technical difficulty encountered was with impurities such as nitrogen, oxygen and water vapor that readily form on the surface during cooling. Early impurity condensation insulates the tip and inhibits neon formation. Impurities can also form after the neon-filled cap is removed. The avoidance of such an overcoating is crucial to the success of the experiment, because ultimately the plasma of interest is formed from the first few micrometers depth of the frozen layer. Good standard vacuum techniques,



including particularly the use of a cryogenic pump capable of preferentially removing such undesirable substances while not pumping inert gases such as neon, proved satisfactory.

### III. PHYSICAL MODEL

It has proven possible to maintain neon layers of useful thicknesses in the 100's of  $\mu\text{m}$  range for multiple laser exposures over a period of at least 10 minutes. That this is feasible even at a temperature of  $10^\circ\text{K}$  in the vapor region is understood from the following simplified and self consistent model.

For a heat of sublimation<sup>11</sup> of  $450\text{ cal/gm-mole}$  and a density of  $1.4\text{ gm/cm}^3$ , a solid neon layer of diameter  $2\text{ cm}$  and thickness  $500\text{ }\mu\text{m}$  will consume  $16\text{ mW}$  of power from the cold tip subsurface if sublimation is complete in  $20\text{ min}$ . According to the manufacturer's information,<sup>10</sup> maintaining the refrigerator assembly at  $10^\circ\text{K}$  consumes approximately  $1\text{ W}$ . The portion of this attributed geometrically to the neon substrate area is  $\sim 10\text{ mW}$ , which is consistent with the total power consumed in sublimation.

A further requirement for neon layer stability is that the thermal conduction rate through the neon layer between the cold tip and the outermost surface (which is undergoing sublimation and cooling) be at least as large as the sublimation rate, in order to assure that excess heat does not build up near the cold tip/neon interface. This heat transfer rate may be estimated from  $\dot{Q} = K \cdot \Delta T \cdot A / D$  for a thermal conduction coefficient  $K$ , a temperature differential  $\Delta T \sim 2^\circ\text{K}$ , a surface area  $A = 3\text{ cm}^2$  and a layer thickness  $D$ . For the solid neon,<sup>11</sup>  $K_{\text{sol}} = 2 \times 10^{-3}\text{ cal/sec-cm-}^\circ\text{K}$  at a temperature of  $10^\circ\text{K}$ ; and for a layer thickness of  $500\text{ }\mu\text{m}$  the heat flux by conduction is  $\dot{Q}_{\text{sol}} = 1\text{ J/sec}$ ,

which is 60 X that needed to maintain quasi-equilibrium during the sublimation process. If, however, a gaseous neon layer grows at an imperfect interface between the frozen neon and the substrate, the thermal conduction coefficient<sup>11</sup> (extrapolated to 10 °K) becomes  $K_{\text{gas}} = 8 \times 10^{-6}$  cal/sec-cm-°K; and a gaseous layer of  $D=100$   $\mu\text{m}$  thickness transmits heat at a very much lower rate of  $\dot{Q}_{\text{gas}} = 5$  mJ/sec, which is a fraction of the sublimation rate. Pressure buildup can then be expected to occur between the cold tip and the neon wafer, with the latter cooled continually by sublimation now from both the outer and the inner surfaces. Apparently this is what we have experienced with exposure to chamber vacuum at cold tip temperatures in the 20 °K and above range, where blowoff of the layer is observed to take place almost instantly. From this a reasonable postulate would be that smoothness of the substrate surface is an important stability factor when operating in this dynamic mode, although this has not been investigated systematically.

#### IV. PLASMA TEST RESULTS

The frozen neon layers formed were irradiated with a flux density of  $10^{12}$  W/cm<sup>2</sup> from a Nd:glass laser operated at 8 J energy with a pulse duration of 4 ns and focused to a spot of 500  $\mu\text{m}$  diameter. The soft x-ray spectrum obtained photographically with a 1-meter grazing incidence spectrograph has been traced with a microdensitometer and the results are shown in Fig. 3. Lines of Ne VI - Ne IX spectra dominate over any trace of condensed impurities or substrate material.

The thickness of the neon layer is somewhat controllable by varying the gas pressure in the neon-filled cavity. By such control it has been possible

to produce very thin layers ( $\leq 10 \text{ }\mu\text{m}$ ), such that spectral lines of substrate material are recorded. This is important for applications which require a plasma mix from different target layers.

## V. SUMMARY

Solid wafer targets consisting of rare gases such as neon for plasma production by focused high power laser beams can now be created on cryogenically cooled surfaces, with thicknesses controlled to the extent that multiple component plasmas can be generated from layers. The layers can also be maintained in a dynamic sublimation mode under high vacuum conditions for sufficient time to complete the plasma experiments; and the factors affecting such a non-equilibrium period are qualitatively understood. The coating procedure is complicated by the low heat capacity of the cold finger employed and by thermal conduction to surrounding walls.

Variations on this basic accomplishment are immediately apparent. Fibers,<sup>13</sup> whiskers or needles can also be coated for targets. Also, patterns of frozen neon can be created by combining the thermally conducting substrate with an insulator and coating only the regions of interest, as we have found that condensation does not readily occur on insulators.

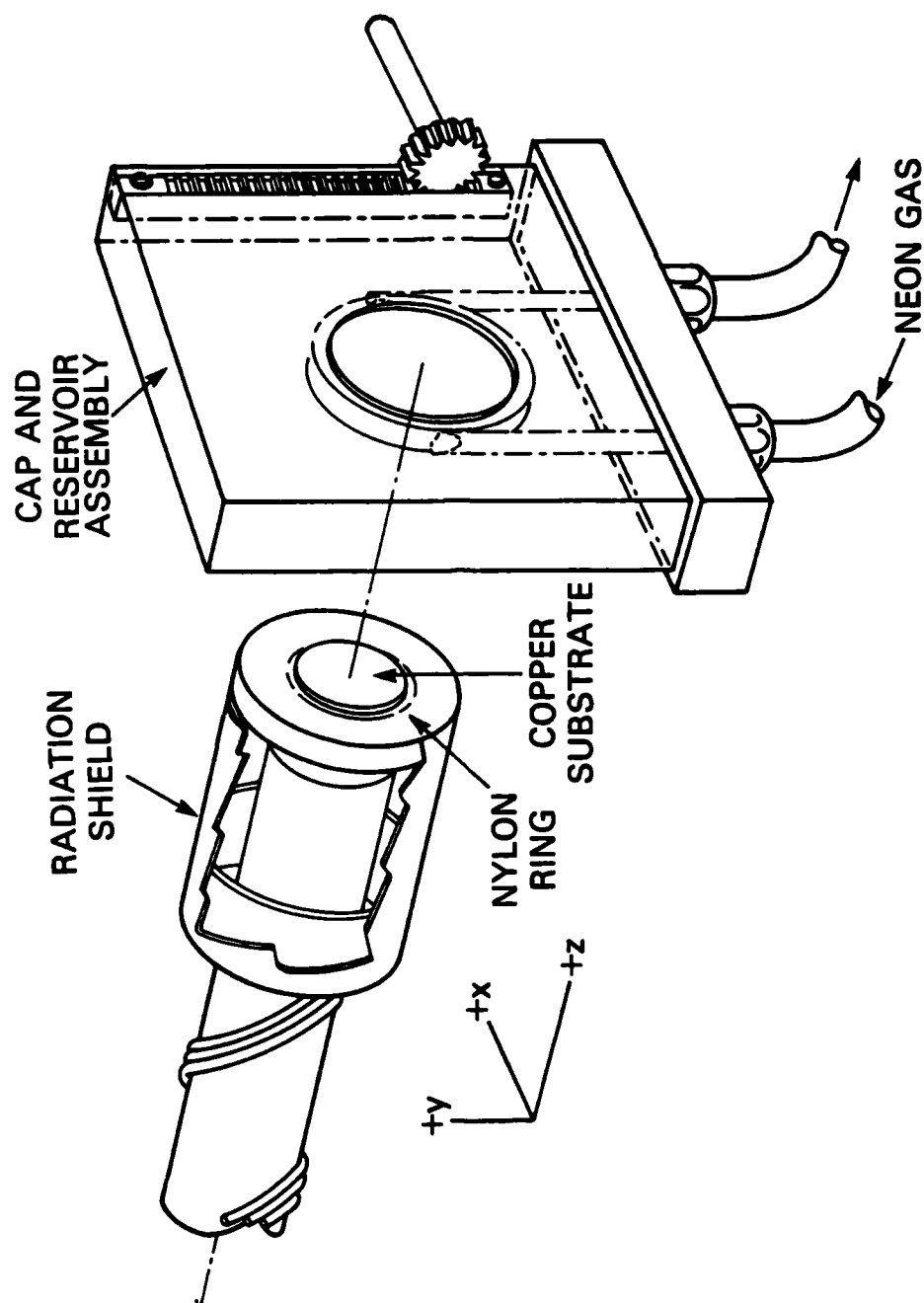


Fig. 1 — Diagram of the apparatus including the high pressure cap, and indicating axial displacements incorporated in the procedures as described in the text.

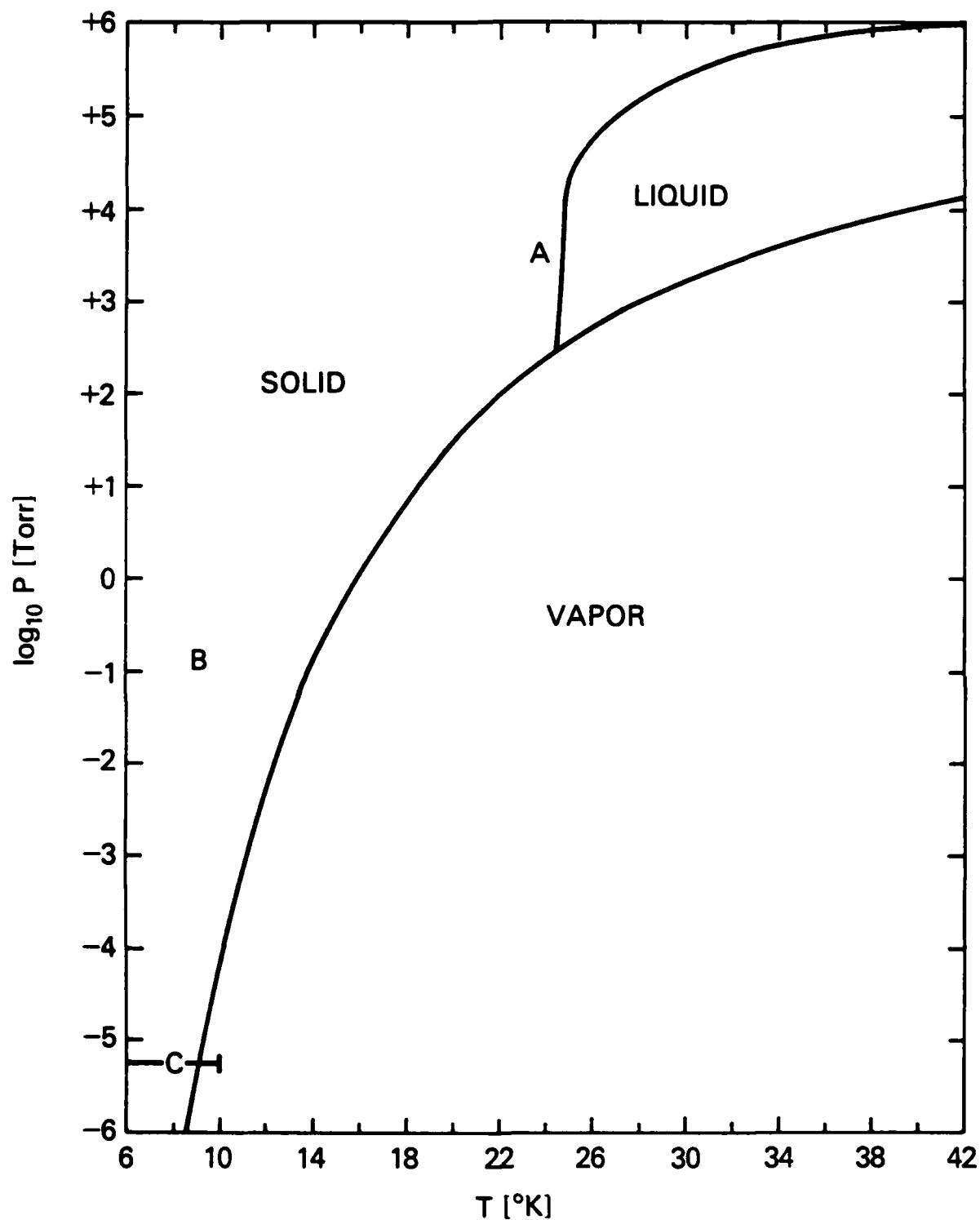


Fig. 2 — Phase diagram for neon, along with typical measured cooling (A), freezing (B) and evacuation (C) cycles.

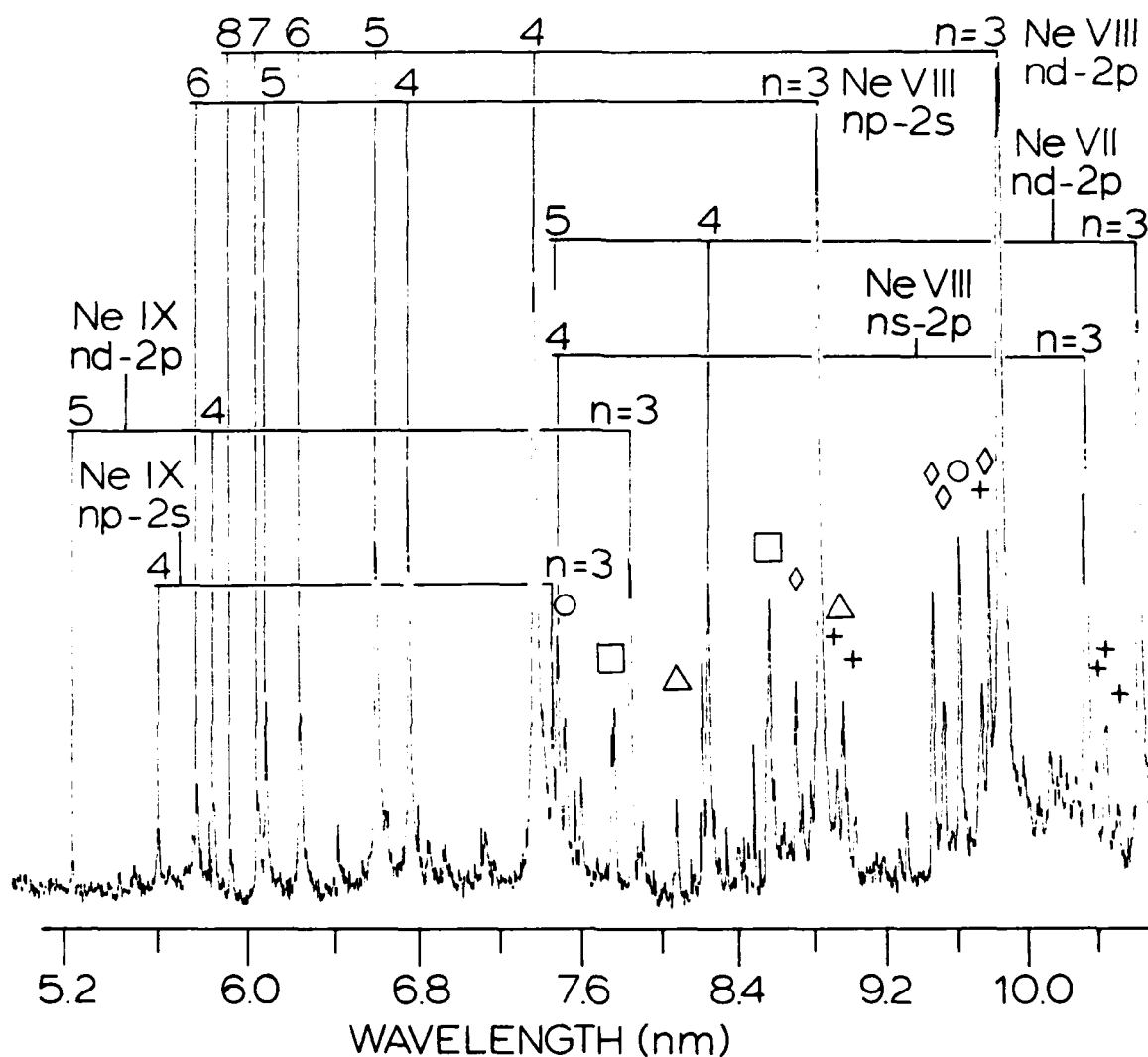


Fig. 3 — Densitometer tracing of a grazing incidence spectrum of neon plasma. Strong Ne VII-IX ( $\text{Ne}^{6+-8+}$  ions) are indicated. Open symbols (except diamonds) refer to specific Ne VII lines. Open diamonds and +'s refer to various weaker Ne VII as well as Ne VI lines, respectively.

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